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Use of Clearance Indexes to Assess Waste Disposal Issues for the HYLIFE-II Inertial Fusion Energy Power Plant Design

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Abstract

Traditionally, waste management studies for fusion energy have used the Waste Disposal Rating (WDR) to evaluate if radioactive material from irradiated structures could qualify for shallow land burial. However, given the space limitations and the negative public perception of large volumes of waste, there is a growing international motivation to develop a fusion waste management system that maximizes the amount of material that can be cleared or recycled.

In this work, we present an updated assessment of the waste management options for the HYLIFE-II inertial fusion energy (IFE) power plant, using the concept of Clearance Index (CI) for radioactive waste disposal. With that purpose, we have performed a detailed neutronics analysis of the HYLIFE-II design, using the TART and ACAB computer codes for neutron transport and activation, respectively. Whereas the traditional version of ACAB only provided the user with the WDR as an index for waste considerations, here we have modified the code to

calculate Clearance Indexes using the current International Atomic Energy Agency (IAEA) clearance limits for radiological waste disposal. The results from the analysis are used to perform an assessment of the waste management options for the HYLIFE-II IFE design.

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1. Introduction

The safe handing of radioactive waste is recognized as vital to ensure protection of human health and the environment. It is also required for the public to accept fusion energy. Previous waste management studies for inertial fusion energy have traditionally used the Waste Disposal Rating to evaluate if neutron activated material from an IFE power plant would qualify for shallow land burial (WDR < 1) [1]. However, given the space limitations and the negative public perception of large volumes of waste (even in the case of low activation materials), the international community has lately focused its efforts on developing a fusion waste management system that maximizes the amount of fusion materials that can be automatically released from regulatory control or "cleared". The IAEA has proposed levels of radionuclides in solid materials below which traditional regulation may be relinquished on the grounds that the associated radiation hazards are trivial [2]. The radiological basis for this guidance is the international consensus on principles for the exemption of radiation sources from regulatory control reached in 1988 [3]. These levels are intended as international reference values and may be seen as those below which radioactive waste can be cleared, i.e. released from regulatory control without further consideration [2].

In this work we have applied the concept of clearance levels to the HYLIFE-II IFE power plant design [4]. Since the times of the original design, safety and environmental characteristics of HYLIFE-II have been analyzed in detail [5, 6]. This design uses a heavy ion driver for indirect illumination of the targets and is based on the concept of thick liquid protection to increase the lifetime of components, thus reducing the volume of radioactive waste. However, this volume would still be significant in the case of the confinement building ($\approx 5 \cdot 10^3$ m^3 of concrete).

In the present work, we have updated the neutronics analysis for HYLIFE-II, obtaining not only the WDRs but also the Clearance Indexes for the different components to determine if any of the power plant structures could be cleared for unconditional use after the full power plant life. For that purpose, we have implemented the calculation of CIs in the activation code using current IAEA limits for radiological waste disposal. The results from the analysis are used to perform an assessment of the waste management options for the HYLIFE-II IFE design.

2. Computational Procedures

A 3-D model of HYLIFE-II was created for the neutronics analysis. The TART Monte Carlo code for neutron and photon transport [7] has been used to obtain the neutron spectrum in 175 energy groups for the different zones of interest in the power plant. The model includes the 60-cm-thick flibe (Li_2BeF_4) inner pocket, the stainless steel type-304 (SS304) chamber/blanket structures with the additional flibe circuits between the first three shells, and a concrete shielding for final focus magnet protection. We have also included a 1-m-thick confinement concrete building at 20 m from the target.

With this model we have obtained the energy-dependent neutron fluxes in the flibe, SS304 and concrete structures. The neutron fluxes have then been used to calculate the activation of materials with the ACAB code [8], a computer program designed to perform activation and transmutation calculations for fusion applications. We have calculated the activation of components following 30 years of full-time operation, obtaining results during the period of irradiation and up to 100 years of cooling after the shutdown of the power plant.

The traditional version of ACAB gives the WDR index for waste considerations. The WDRs are used to determine if a particular component can be disposed via shallow land burial. They are calculated by ACAB using the specific activity limits given by Fetter et al. [9]. The WDRs are calculated for each radionuclide, and summation over all radionuclides provides a single value that allows components to be compared to one another. A WDR less than unity indicates that a component would qualify for shallow land burial (assuming that regulations for fusion-relevant radionuclides are implemented on the same basis as those that have been implemented for fission waste). However, given the space limitations and the negative public perception of large volumes of waste, shallow land burial is not necessarily the best method of waste disposal.

Thus, here we have implemented the calculation of Clearance Indexes in ACAB using the current IAEA clearance limits. The way these indexes are calculated and their meaning are explained next.

3. Calculation of Clearance Indexes

The Clearance Index (CI) for a material containing a single radionuclide n is calculated by Equation 1, where A_n is the activity due to the nuclide and L_n is the IAEA clearance level for the nuclide. If CI ≤ 1 then it is possible to clear the material.

$$CI = \frac{A_n}{L_n} \tag{1}$$

Most materials contain a mixture of radionuclides, and in this case the Clearance Index is calculated by Equation 2. Again, clearance is possible if CI ≤ 1.

$$CI = \sum_i \frac{A_i}{L_i} \tag{2}$$

In Equations 1 and 2, activities and clearance levels have units of $Bq \cdot kg^{-1}$. Reference [10] gives clearance values for a number of nuclides and a general formula that can be used to calculate the level for any other nuclide. The formula is given in Equation 3,

$$L_i = \min\left\{\frac{1000}{E_{\gamma,i} + 0.1 \times E_{\beta,i}}, \frac{D}{e_i^{inh}}, \frac{D}{e_i^{ing} \times 10^2}\right\} \tag{3}$$

where: $D = 20\ mSv \cdot y^{-1}$, i.e. the dose limit for radiation workers [11], and for the i^{th} nuclide, the other quantities are: $E_{\gamma,i}$ - effective photon emission energy (MeV); $E_{\beta,i}$ - effective beta decay emission energy (MeV); e_i^{inh} - committed effective dose equivalent from inhalation ($Sv \cdot Bq^{-1}$) and e_i^{ing} – committed effective dose equivalent from ingestion ($Sv \cdot Bq^{-1}$). Note that these quantities are available in the EAF_DEC-99 and EAF_HAZ-99 libraries [12, 13]. Equation 3 was used to calculate L_i values for all nuclides not given explicitly in reference [10].

4. Results

Using the results from neutron transport and activation calculations for the HYLIFE-II design, we have obtained the waste disposal indexes for the different components. First, the WDRs were calculated for the coolant (flibe), blanket structures, inner shielding and confinement building. Table I shows not only the WDR but also the life-cycle waste volume (LCWV) for each component. It can be observed that all of the structures would qualify for shallow land burial (WDR < 1), and the waste volume is dominated by the 5300 m^3 of concrete from the confinement building.

Figure 1 shows the Clearance Index for the different reactor structures as a function of the time after shutdown. It can be observed that in the cases of the stainless steel structures, the flibe coolant and the inner shielding, the best waste management option would still be shallow land burial, given that clearance of these materials is not possible (CI > 1). The confinement building, however, reaches the clearance level after about one year of cooling. Since the volume of the concrete building dominates the total life-cycle waste volume of the power plant, this is a significant S&E advantage for HYLIFE-II. Also, the cooling time for the building to reach the clearance level (~1 year) is quite short compared to the anticipated decommissioning time for the plant.

5. Conclusions

Previous IFE studies have traditionally used the WDRs as waste disposal index in order to determine if a particular component qualifies for shallow land burial disposal. However this may not be the best waste management option if one has to dispose of relatively large volumes.

In this work, we have introduced the concept of Clearance Indexes in order to determine if components of the HYLIFE-II inertial fusion energy power plant could be cleared from regulatory control.

We modified the activation code ACAB to include the calculation of Clearance Indexes, and we calculated both the WDRs and CIs for each component of the power plant. Although all of the structures would meet the requirement for shallow land burial (WDR < 1), the total volume is significant and undesirable. On the other hand, the results on CIs show that in the case of the confinement building, which dominates the total volume of the waste stream, clearance would be possible after about one year of cooling following the shutdown of the plant.

This result represents a very attractive option for waste management considerations of the HYLIFE-II power plant, as it means that the material could be released from regulatory control for unconditional re-use after a relatively short period of cooling. Further work on S&E issues for IFE should focus on maximizing the amount of material that qualifies for clearance, as the preferred option for waste management.

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Equation 1

$$CI = \frac{A_n}{L_n} \qquad (1)$$

Equation 2

$$CI = \sum_i \frac{A_i}{L_i} \qquad (2)$$

Equation 3

$$L_i = \min\left\{\frac{1000}{E_{\gamma,i} + 0.1\times E_{\beta,i}}, \frac{D}{e_i^{inh}}, \frac{D}{e_i^{ing}\times 10^2}\right\} \qquad (3)$$

Table I. WDRs and life-cycle waste volumes (LCWVs) for the different components of the HYLIFE-II design.

Component	WDR	LCWV (m^3)
SS304 blanket structures	8.7E-01	3.1E+01
Flibe coolant	2.3E-03	1.2E+03
Inner shielding	3.0E-05	9.1E+02
Confinement building	2.7E-05	5.3E+03

Figure 1. Clearance indexes for the different components of the plant as a function of the cooling time